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Role of two-stage strike slip faulting in the tectonic evolution of the Doseo depression in the central Africa rift system

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Doseo depression of Central African Rift System is an important onshore frontier area for oil and gas exploration in Africa, with rift development characterized by the dual control of fault-depression development and strike slip faulting. According to the latest drilling and seismic data in recent years, through the fine seismic interpretation, the calculation of paleo-fault throw and fault growth index and the method of balanced profile cross-section restorations, the fault characteristics and tectonic setting of Doseo depression are analyzed in detail, especially the fault activity, tectonic evolution and genetic mechanism of two large-scale strike slip movements in Doseo depression. The results show that the Doseo depression experienced five main tectonic phases, including two stages of strike slip tectonic movements with different mechanisms. The first stage is characterized by strike slip tectonic movements under tilting extension, which controls the overall structure of the depression. The second stage is characterized by strike slip tectonic movements under transform compression, which play an important role in the formation of some inversion structures and SW-NE trending anticlines and faulted anticlines. The superposition of an early faulted-depression and two later stages of strike slip tectonics led to current pattern of Doseo depression.

KEYWORDS

central African shear zone, Doseo depression, tectonics evolution, strike slip, structural inversion

1 Introduction

Africa is a key area for oil and gas exploration and development in the world. As established by exploration, the north and west of Africa are rich in oil and gas resources. However, the depressions developed along the Central African Shear Zone (CASZ) in the Central African continent have been relatively under-explored and are an important onshore frontier for oil and gas exploration in Africa (Dou et al., 2022). Compared with extensional rift basins that are associated with large amounts of discovered oil and gas, little oil and gas has been found in the Doseo depression and other strike slip basins (Zhang and Qi, 2007; Dou et al., 2011). Previous studies on such basins are sparse, especially research on basic geological problems such as basin structure and structural characteristics, which seriously restricts exploration in this area.

Structure and evolution characteristics play an important role in controlling the generation, migration, and accumulation of oil and gas (Dou et al., 2011; Lei and Liu, 2017; Zhang et al., 2020). A Doseo depression is formed under the dual control of fault-depression development and strike slip faulting, and its late structures are multi-stage and diverse (Fairhead et al., 2013). Earlier studies found that the Doseo depression experienced intense strike slip movements controlled by the activity of the Central African Shear Zone (Kong et al., 2018; Fairhead, 2020), but the timing, fault development characteristics, evolution characteristics, and genetic mechanism of these two stages of strike slip are still unclear. Based on the tectonic evolution of the Central African Shear Zone, this paper analyzes the fault structural characteristics of the two stages of strike slip movement in the Doseo depression and describes its tectonic evolution and the genetic mechanism through seismic data interpretation. It uses balanced cross-section restoration, fault growth index, and paleo-fault throw research to guide further oil and gas exploration and deployment in the strike slip basin.

2 Geological setting

The Central African Shear Zone is an intracontinental dextral strike slip system with a length of about 2,000 km extending NE-SW in the Central African continent (Figure 1B). It extends from the Gulf of Guinea in western Africa and passes through Cameroon, southern Chad, and the Central African Republic to Sudan to the east. The Borogop uplift and Gongo uplift developed along the Central African Shear Zone, and the basin is divided into the Doba depression, Doseo depression, and Salamat depression from west to east (Genik, 1992; Genik, 1993; Zhang et al., 2021).

The Doseo depression is located in the middle of the south Chad Basin, nearly parallel to the Central African Shear Zone. It is about 60–80 km in the N-S direction and about 450 km in the E-W direction, covering an area of approximately 50,000 square kilometers. It is adjacent to the Doba depression in the west and the Salamat depression in the east. In map view, it is a rhombic depression in the NEE-SWW direction (Lv and Zhao, 2018). The Doseo depression belongs to the Central African Rift System (CARS), and its formation is controlled by the evolution of Central African strike slip faults (Figure 1C). From ancient times to the present, subsidence in the Doseo depression has resulted in the deposition of the Mangara Formation, Kedeni Formation, Doba Formation, Koumra Formation, and K_2 Formation.

Previous studies of the Doseo depression have acquired 2D seismic data of about 25,000 km in line-length, 3D seismic data is about 1,200 square kilometers, 24 wells have been drilled, and 11 oil and gas discoveries have been obtained. The overall exploration degree of the depression is low, but the potential is large (Figure 1D).

3 Stratigraphy

According to the interpretation of the regional tectonic events, fault characteristics, and seismic data of the Central African Rift System, and in combination with the work of Guiraud and Bosworth. (1997), the Doseo depression mainly developed in the Precambrian, Cretaceous, Paleogene, Neogene, and Quaternary, resulting in a set of terrigenous clastic deposits (Reynolds and Jones, 2004). There are three main regional unconformities from bottom to top (Wu et al., 2018; Fairhead, 2020), which are the basement and lower Cretaceous unconformity, lower Cretaceous and Upper Cretaceous unconformity, Cretaceous, and Cenozoic unconformity. There are obvious differences in the structural deformation characteristics of the layers between these unconformities (Figure 2).

The lithology of the Doseo depression is mainly thick sandstone, shale with siltstone, and sandstone with thin shale (Figure 2). In the early Cretaceous from 145–125 Ma, the Mangara Formation formed, mainly composed of sand mudstone interbedded deposits, with a deposition thickness of up to 3 km. From 125–111 Ma, the Early Cretaceous L. Kedeni Formation to Doba Formation formed in the Doseo depression is mainly composed of mudstone with a small amount of sandstone, and the sedimentary thickness is about 2 km. From the late Early Cretaceous, from 111 Ma to the present, the proportion of mudstone strata gradually reduced, becoming sandstone dominated, with a thickness of 2 km. In general, from the bottom to the top of the formation, the specific gravity of sandstone increases, and that of shale decreases (Zhang et al., 2021).

4 Method and samples

This analyses the development of the Doseo depression based on previous research results and regional research data. Seismic horizon labeling was carried out using well data before the interpretation of the seismic section. By interpreting the 2D and 3D seismic data, we can further study the fault characteristics, draw the fault plane distribution map, and calculate the paleo-fault throw and fault growth index of the main fault zones in the study area for quantitative analysis of fault activity.

Paleo-fault throw is the difference in the thickness of the sedimentary layer between the hanging wall and footwall of fault in a certain period (Cartwright et al., 1995), which is used to judge the activity of the fault: the larger the throw is, the stronger the fault activity is (Ran et al., 2019). Assuming that, for a normal fault, “A” represents the thickness of the hanging wall stratum in a certain period, and “a” represents the thickness of the footwall stratum in the same period, the Paleo-fault throw is calculated as follows:

$$\text{Paleo} - \text{fault throw} = A - a.$$

The fault growth index is the ratio of the sedimentary layer thickness of the hanging wall and footwall of a fault in the same geological history period. The growth index is calculated as follows:

$$\text{Fault growth index} = A/a.$$

When the fault growth index is 1, the fault is inactive. When the fault growth index is greater than 1, it is directly proportional to the fault activity. When the fault growth index is less than 1, it indicates that the fault property is reversed. The relative value of the fault growth index can reflect the fault activity cycle and migration of fault activity in space and time (Lei, 2012).

Since the Doseo depression is affected by factors such as sediment compaction, erosion, and denudation, it is likely that there are some errors in the analysis of paleo-fault throw and fault growth index, two methods of analysis that have merits as well as limitations. In this study, the calculation method was selected

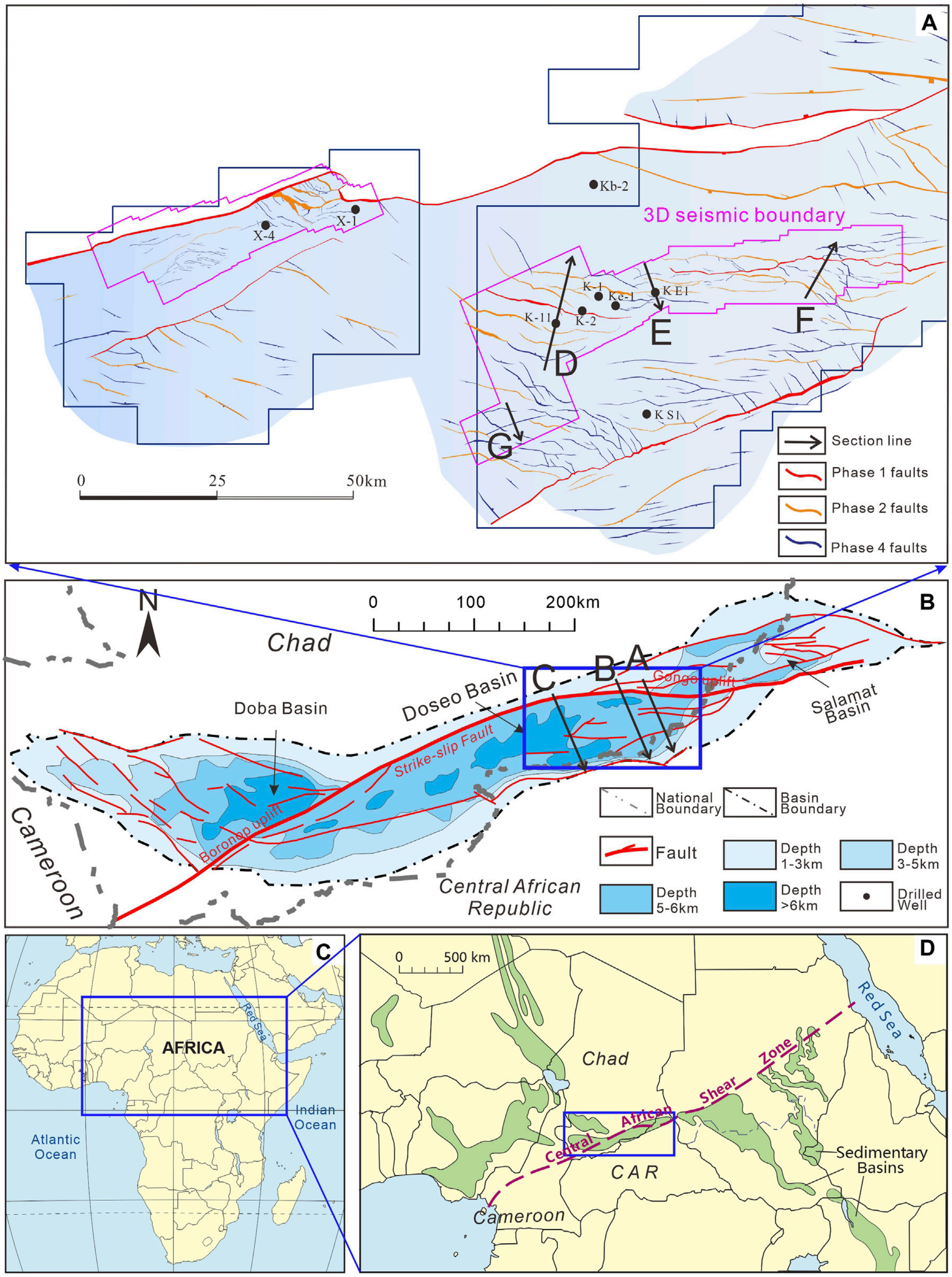

FIGURE 1
Structure and basement burial depth in Doseo depression. **(A)** Fracture system diagram of the study area. **(B)** Structural location of Doseo depression. **(C)** Geographical Location Map of Africa. **(D)** Location of Doseo depression in Central African Shear Zone.

according to the characteristics of faults, and the two methods were combined to minimize the impact of errors and more objectively reflect the changes in fault activity in the study area.

To study the tectonic evolution process of the Doseo depression, balanced cross-section restorations were used to analyze its evolution. By gradually restoring the deformed section to the

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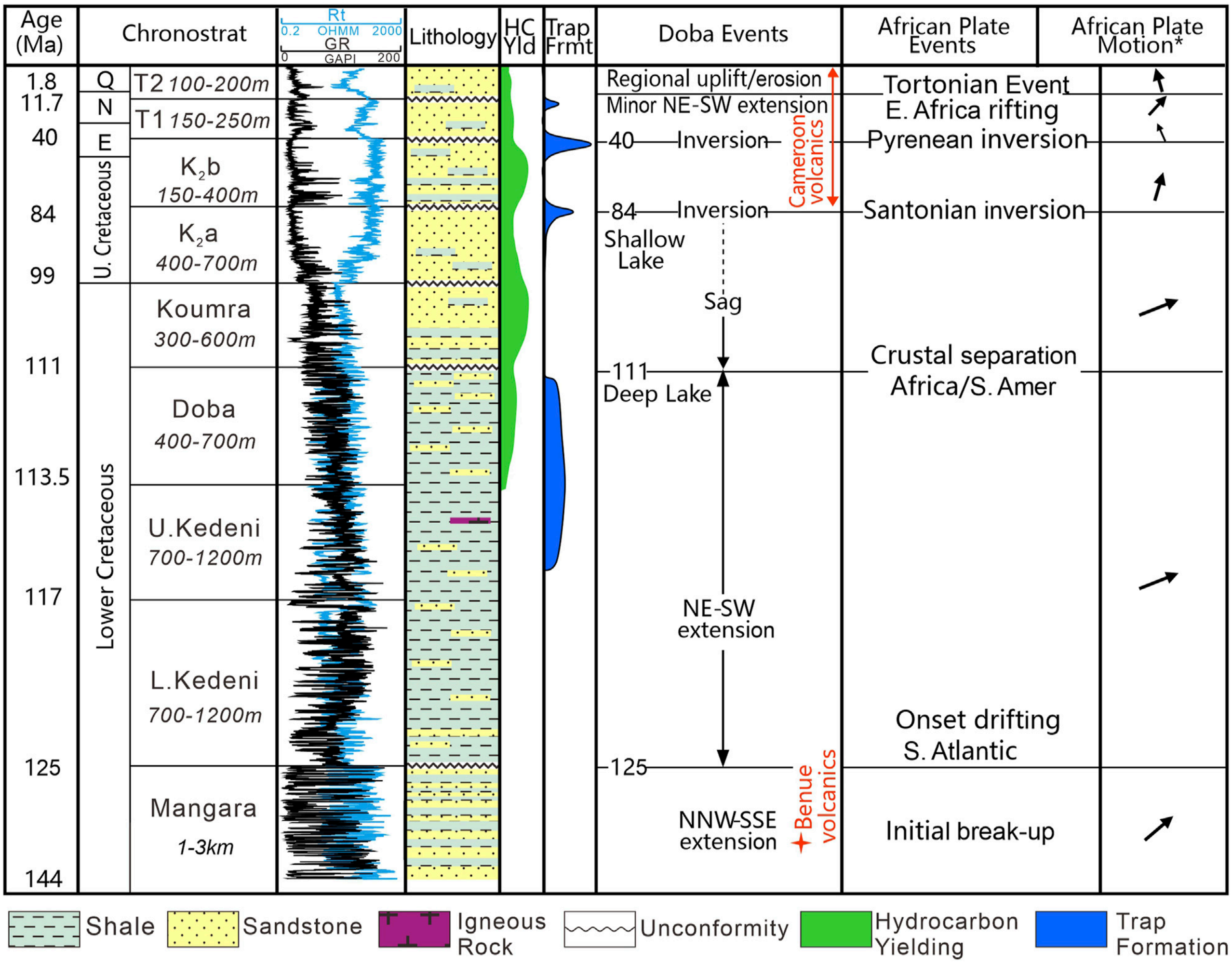

FIGURE 2
Stratigraphic column of Doseo depression (modified according to Guiraud and Bosworth, 1997).

original state without deformation, we obtained quantitative information including tectonic deformation features and strain variables at each tectonic stage (Wright et al., 2020) and then analyzed the evolutionary history of tectonic deformation, which provides a scientific basis for regional structural interpretations (Zhou, 2005). The best section parallel to the maximum tectonic migration direction was selected and the time domain section was converted into the depth domain section according to the time-depth data of well Ke-1. Each stratigraphic unit was back-stripped layer-by-layer from the youngest to oldest with 3D Move software, and finally, the tectonic evolution section of each stage was obtained.

5 Results

5.1 Doseo depression structure

The Doseo depression is a complex faulted rift basin affected and formed by extension (Figure 1B), strike slip, and compressional tectonic environments (Fairhead, 2020). The main structure of the basin is a long and narrow dustpan-like faulted depression with a north-south zonation and east-west block structure. The basin is broadly characterized by one depression between two uplifts to form the northern uplift, the central Doseo depression, and the southern uplift. The Doseo depression in the middle is the main body, which can be divided into five structural units: the northern steep slope zone, the northern depression, the central low uplift zone, the southern depression, and the southern gentle slope fault terrace (Figure 3). The northern steep slope zone mainly develops reverse compression anticline structures, and the southern gentle slope fault terrace mainly consists of fault block structures (Kong et al., 2019). The Doseo depression is controlled by the Central African Shear Zone and distributed in a NE-SW narrow strip.

Multistage active faults are developed in Southern Chad Basin and Doseo depression (Figure 1B), and the boundary faults are different in different tectonic periods (Dou et al., 2022). The early basement normal fault in the Doseo depression was superimposed with strike slip activity in the late stage (Fairhead, 2020). The boundary faults and some internal faults were mainly active in the Mangara Formation sedimentary period, which controlled the

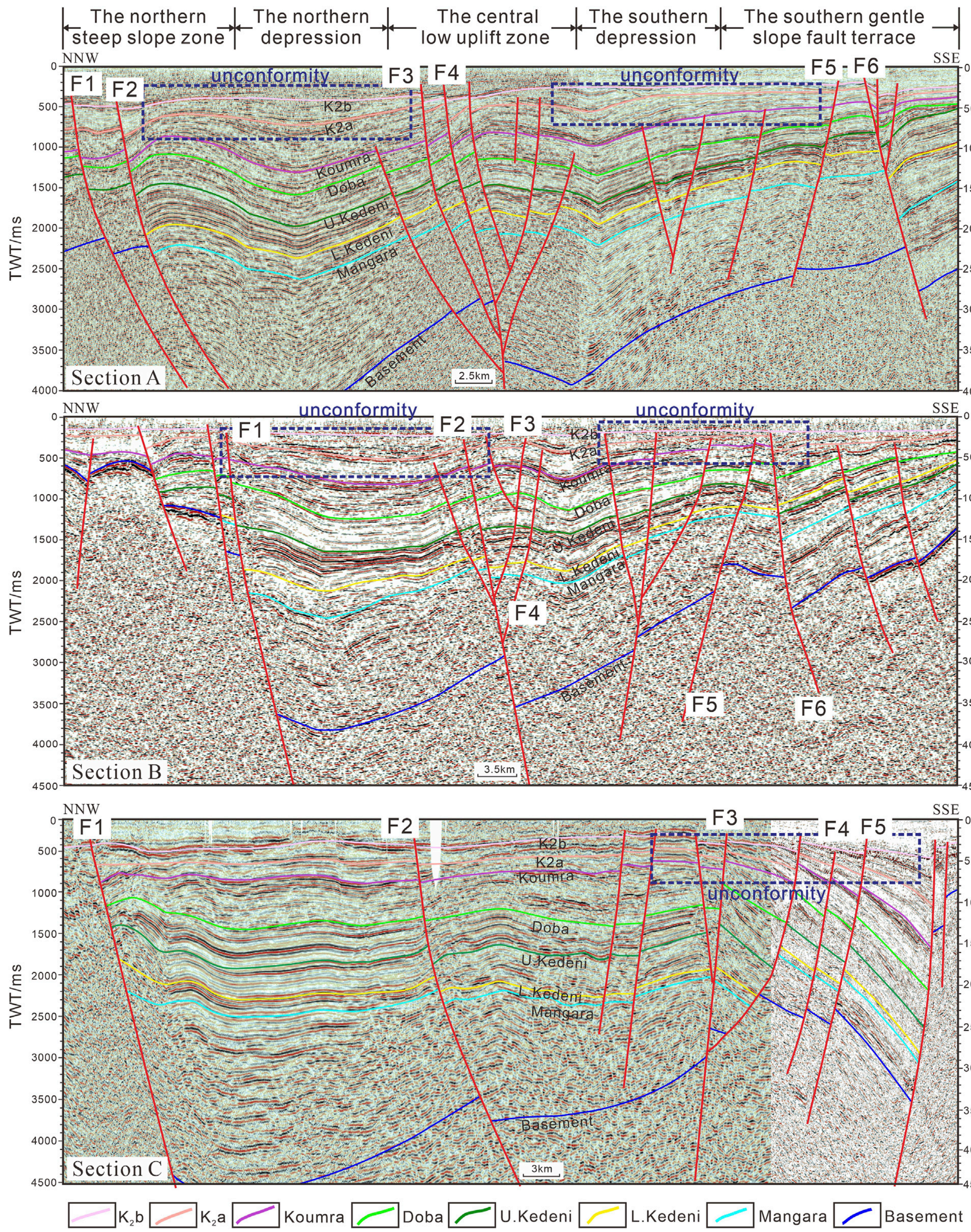

FIGURE 3
Interpretations of seismic profiles of Doseo depression [Section **(A–C)** in Figure 1B].

deep rift structure of the Doseo depression. The faults in the depression are mainly active in Kedeni Formation -K_2 Formation sedimentary period (Figure 3). The fault displacement of these internal faults is relatively small, the dip angle is relatively steep, and the secondary faults are less developed. The whole set of strata are uniformly compressed and deformed from top to bottom, and the main body of the depression has an obvious double-layer structure, that is, the deep North Fault (F1 and F2) and South super dustpan half graben fault depression structure superimposes the shallow depression structure (Figure 3).

By selecting three sections of the Doseo depression perpendicular to the Central African shear zone from west to east, the faults in the depression have the characteristics of multi-stage activity in the vertical direction (Figure 3). In the early stage, the depression was extensional and developed normal faults (Fairhead, 2020). In the later stage, affected by strike slip and undergoing structural inversion, the strata were uplifted and denuded, especially in the northern and western depression zones of the central depression zone. The northern depression zone has a North-South double fault structural pattern, and angular unconformity and strata denudation can be seen at the top of the seismic profile (Figure 3). During the Kedeni Formation- Koumra Formation sedimentary period, a large number of normal faults and normal strike slip faults were developed in the depression, some of which controlled sedimentation, and the fault displacement was generally small (Figure 3). In the late Cretaceous K_2a Formation sedimentary period, the fault activity weakened. At the end of the K_2a Formation sedimentary period, the northern boundary fault of the Doseo depression was reversed, forming a fault anticline, and the southern part of the depression was greatly uplifted and denuded, forming an angular unconformity (Figure 3). At the end of the Cretaceous, strike slip and tectonic activities occurred in the boundary fault of the Doseo depression and the fault zone in the middle of the depression (Fairhead et al., 2013), which induced the development of a large number of echelon oblique secondary faults intersecting with base faults in the depression (Figure 7E), forming flower structures and arch tension anticlines.

5.2 Structural style of Doseo depression

Doseo depression experienced compressional, strike slip, and extensional stages (Kong et al., 2019; Fairhead, 2020). Under the influence of these three stages, the Doseo depression mainly developed five structural styles: inversion structure, strike slip structure, fault terrace, graben-horst system, and domino structure (Figure 4). Based on the characteristics of the depression structure and planar fault distribution, combined with the planar distribution characteristics of the regional fault system map, it can be concluded that the overall structural characteristics of the Doseo depression have the rule of planar Zoning: from north to south, it can be divided into northern fault fold structural belt, central strike slip structural belt and southern extension structural belt. A nearly E-W trending main fault developed in the north of the Doseo depression (Figure 1A). Due to the late compressive and torsional tectonic stress, the hanging wall strata of some large high angle normal faults are folded and deformed (Section A F2 in Figure 3). The structural style developed near the main fault is an inversion structure (Figure 4). As the Doseo depression experienced strike slip tectonic activities in a later stage, a series of strike slip structures were inherited and developed on the pre-existing normal fault in the middle of the depression. Of these strike slip structures, flower structures are the most prominent. These faults are arranged en-echelon in map view (Figures 1A, 4) and there is little evidence for syn-depositional faulting. The structural styles mainly developed in the south of the Doseo depression are half graben, fault terrace, and domino structures. The difference between them lies in whether the fault blocks between faults rotate. Some graben-horst systems are also developed locally, and the styles are arranged in parallel in map view (Figures 1A, 4).

5.3 Fault activity

Under the influence of multi-stage tectonic activities, Doseo depression formed its unique structural characteristics. To dissect the active characteristics of the faults, be familiar with the active periods of faulting, and interpret fault and basin evolution, we selected a total of 17 scattered marker faults on the three interpreted sections from west to east of the Doseo depression (Figure 3), calculate their paleo-fault throw in different sedimentary periods, and compare and analyze the overall activity of the faults (Figure 5).

As shown in Section B (Figure 3), the depression presents an asymmetric double fault structure on the profile, that is, large boundary faults F1 and F6 are developed on the north and south sides of the depression. In addition to these two boundary faults, there is also a deep and large fault F2 penetrating the basement in the central part of the depression. Its occurrence is similar to the left boundary fault F1 of the depression (Figure 3). In terms of the number of faults, the fault density developed between the two large faults F1 and F2 is less than that between the faults F2 and F6. The paleo-fault throw of faults F1 and F2 was large during the deposition of the Mangara Formation, which has a thickness of more than 500 m (Figure 5). The paleo-fault throw during other depositional periods was relatively small, indicating that the two major faults were strongly active during the deposition of the Mangra Formation, and the paleo-fault throw of fault F2 was negative during the deposition of the K_2a Formation. It is speculated that the fault properties of F2 changed during this period, and the fault had a strong reversal. The activity of boundary fault F6 was relatively strong during the deposition of the Mangara Formation and the U. Kedeni Formation (Figure 5). During the deposition of the K_2b Formation, the paleo-fault throw of fault F6 became negative, and therefore we suggest that fault F6 also reversed during this period (Figure 5). The paleo-fault throw of faults F3, F4, and F5 was relatively small, and F5 reversed on a small scale during the deposition of the K_2a Formation (Figure 5).

The fracture characteristics of the profile in Section A are roughly similar to those in Section B (Figure 3). The boundary fault controls the development of the depression, and the strike slip fault is developed in the middle. The profile combined with the location of the survey line also shows that the faults on the south side of the Doseo depression are more developed (Figures 1A, 3). While the large faults in the boundary and central part of the depression were strongly active during the deposition of the Mangara Formation sedimentary period, other faults were all late active (Figure 5), and their activity was relatively stable and gradually weakened. Fault F3 and F4 have negative paleo-fault throw values in the K_2a Formation sedimentary period, and F6 has negative values in the K_2b Formation sedimentary period (Figure 5), which also indicates that faulting in the depression during deposition of the K2a and K2b Formations reversed.

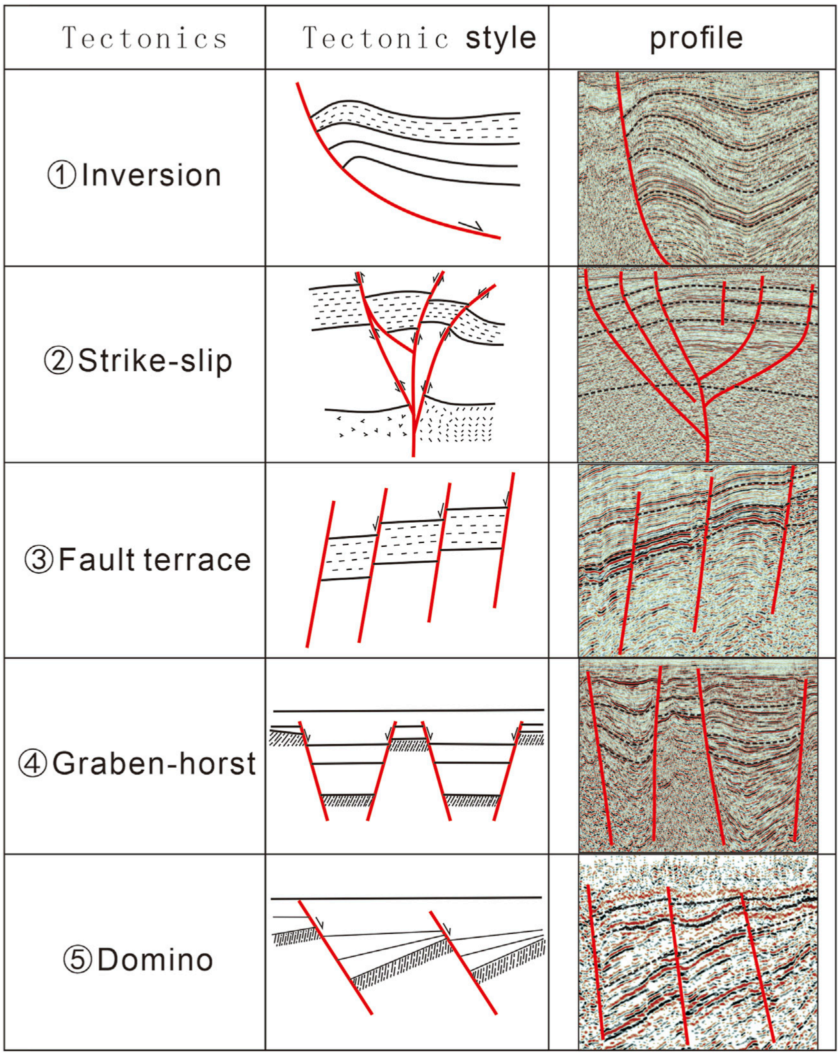

FIGURE 4
Structural styles of faults in Doseo depression.

The fault activity characteristics of Section A and Section B are similar: the boundary fault of the depression and the deep and large fault in the depression are strongly active during the deposition of the Mangara Formation (Figure 5) and control the deep rift structure of Doseo depression. Most of the other faults in the depression are active during the deposition of the Kedeni and Doba Formation, and the fault displacement is relatively small. In the late stage, some faults in the middle and south of the depression reversed.

Section C survey line is located in the west of Section A and Section B (Figure 1B), which is relatively far away, so its section characteristics are also quite different. The left boundary fault F1 controls the spatial distribution of the depression. On the whole, the profile still shows that the fault density of the south side is greater than that of the north side (Figure 3), indicating that the number of faults in the map view increases from north to south (Figure 1A). The activities of F1, F2, and F3 in the early Mangara Formation sedimentary period and the L. Kedeni Formation sedimentary period are relatively strong, and the later activity decreases until fault activity on F1 and F3 increases during deposition of the K2 Formation, and the F2 fault reverses (Figure 5). Faults F4 and F5 are produced during the development of the depression, with small activity and scale. In general, the overall activity of faults in Section C is weaker than that in Section A and Section B (Figure 5).

In general, the boundary fault (Section B F1 in Figure 3) and the central deep fault (Section B F2 in Figure 3) in the Doseo depression were active early, with high activity intensity, and other internal faults inherited or later formed. The overall activity of the faults east of the depression has been relatively stronger than that in the west. The number of faults in the south of the depression is more than that in the north, and most of them are small faults with weak activity. During the K_2a and K_2b Formation depositional periods, the paleo-fault throw of some faults was negative. It is inferred that the inversion occurred in the later stage of the development of the depression, and the inversion mainly affected the faults in the middle and south of the depression.

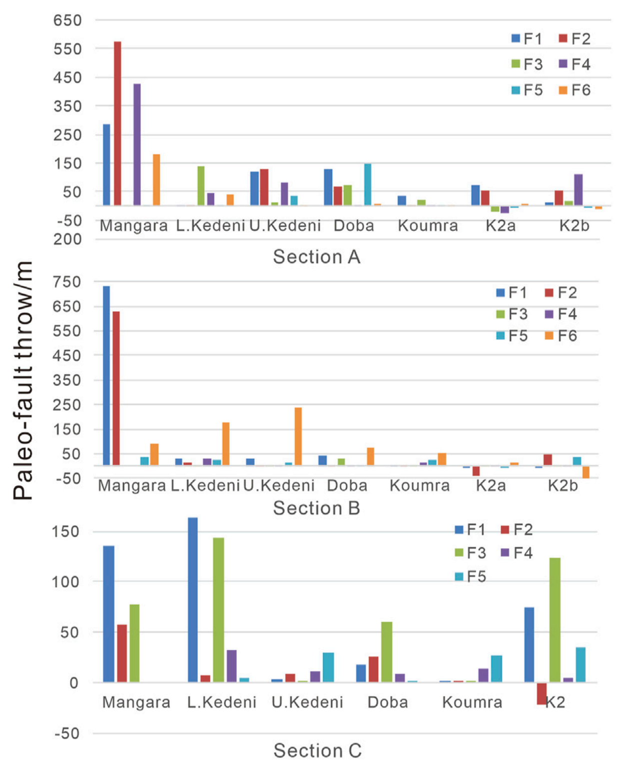

FIGURE 5
Paleo-fault throw histograms showing the throw accumulated on the analyzed faults during the deposition of different formations [Sections **(A–C)** in Figure 1].

5.4 Tectonic evolution of Doseo depression

The formation and evolution of the Doseo depression are closely related to the activities of the Central African Shear Zone. The Doseo depression is located in the Midwest of the Central African Shear Zone. The Central African Shear Zone experienced multi-stage tectonic activities, including strong and weak strike slip. Controlled by the intensity of the Central African Shear Zone, the Doseo depression also undergoes multistage tectonic evolution (Fairhead, 2009; Huang et al., 2021).

Based on the analysis of regional unconformities and the recovery of the regional tectonic stress field, this paper divides the tectonic evolution stages of Doseo depression using the method of balanced cross-section restorations (Figure 6). When considering these results in the context of the past and present regional tectonic setting, this approach unravels the evolution of the Doseo Depression, which evolves between stages of extension, strike slip, and structural inversion. The tectonic evolution of Doseo depression can be divided into five stages (Figure 6):

(1) Early Cretaceous rifting period (Mangara Formation sedimentary period). During the sedimentary period of the Mangara Formation in the Early Cretaceous, the South Chad Basin was stretched in an NNW-SSE direction and developed a fault depression. The balanced cross-section restoration (Figure 6) demonstrates that during this period, the north side of the stratum was deeply concave under the control of the boundary fault, and typical syndepositional phenomena occurred. The rest of the faults were sporadically developed, with low fault density but the large scale and branch faults were not developed. Faults jointly control the deposition of strata. The depression was mainly controlled by three major faults, which are the boundary faults on the north and south sides and the deep and large faults in the middle of the depression, controlling the overall structure of the depression. At this time, the sedimentary center of the depression was located in the east of the depression, with a thickness of up to 4,000 m, thinning to the west, mostly 1,000–2,000 m (Kong et al., 2019). With the continuation of north-south extension, sedimentation expanded, gradually expanding to the west, with a sedimentary thickness of 500–1,000 m.

The depression has well-developed faults. Drilling in the depression reveals that thick lower Cretaceous strata were deposited in the depression during this period, with a thickness of 5,000–6,500 m. This period is an important period for the formation of the depression. Sedimentary fillings account for 80% of the total sediment thickness in the depression. The study of sedimentary facies shows that lacustrine sediments are widely developed during this period, and the lithology is mainly shale (Kong et al., 2019). It is also an important period for the development of high-quality source rocks in the depression.

(2) Early Cretaceous fault depression period (Kedeni Formation-Doba Formation sedimentary period). During this period, due to the expansion of the South Atlantic and the superposition of transform faults, the Central African Shear Zone was activated (Binks and Fairhead, 1992). Southern Chad Basin as a whole is located in a dextral strike slip shear zone (Fairhead, 2020). During this period, the Doseo depression is a dextral strike slip pull apart depression, and the depression is controlled by boundary extensional strike slip faults. Our cross-section restoration (Figure 6) shows that three groups of strata were deposited in this period: L. Kedeni Formation, U. Kedeni Formation, and Doba Formation. The faults in this period mainly developed in the middle and south of the depression, and the density of the faults increased and the scale decreased. The faults in the middle part are inherited and developed, forming a strike slip structural style (Figure 6). Except for the boundary faults on the north and south sides, there are no obvious syndepositional features on other faults. During the continuous evolution of the Deseo depression, the shape of the boundary normal fault changed from planer to curved.

With the rapid separation of the African plate and the South American plate (Guiraud et al., 2005), we interpret that the regional dynamics of tectonic deformation have changed. The North-South stretching of the Central South Africa block and the northeast Africa block switched to a dextral strike slip motion, and the depression began to form two sedimentary centers in the East and West. The sedimentary thickness in the East is large, up to 1,000–1,500 m, and that in the west is thin, mostly 500–1,000 m (Kong et al., 2019).

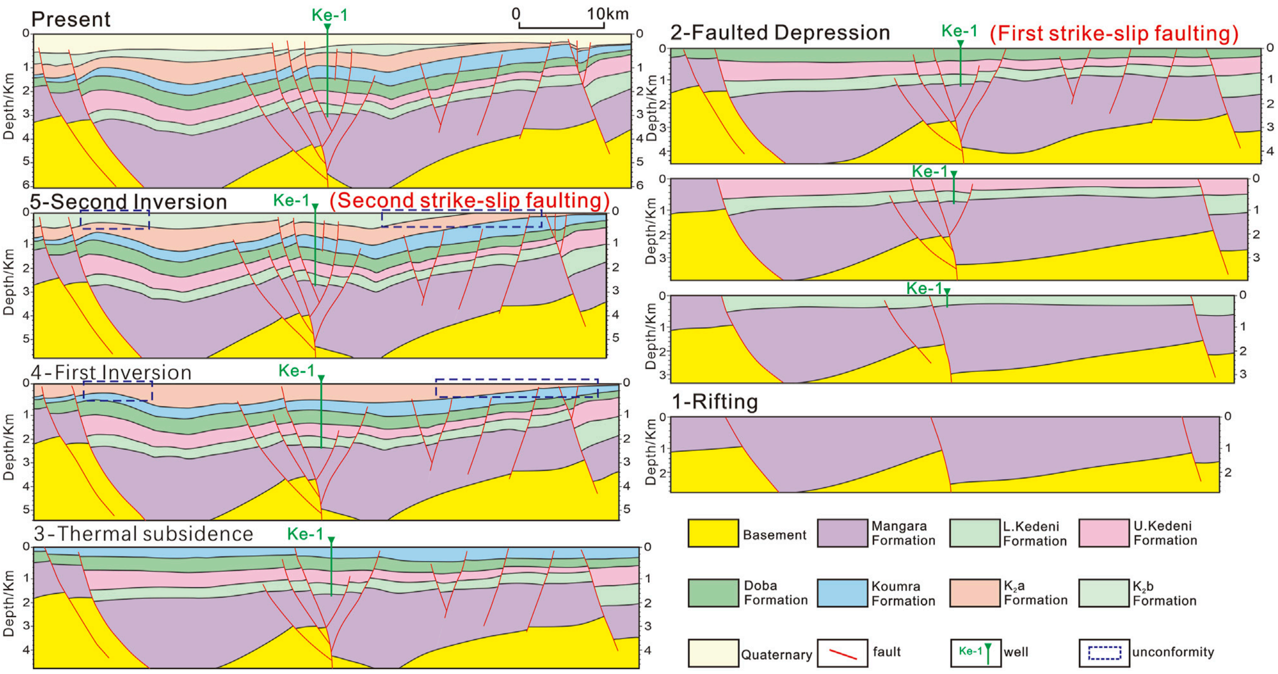

FIGURE 6
The regional geodynamic and tectonic environment changed (Section A in Figure 1).

(3) Late Cretaceous thermal subsidence period (Koumra Formation sedimentary period). In the early Late Cretaceous, the strike slip motion of the Central African Shear Zone became weaker, and the torsion tension of the Doseo depression became weaker. In response, thermal subsidence occurred in the study area (Zhang et al., 2015; Fairhead, 2020), with a slow sedimentation rate and sedimentation occurring over a wide area, and the sedimentation center gradually moved southward to the Midwest of the depression (Lv and Zhao, 2018). The depression began to enter the stage of slow subsidence, producing gently sloping paleo-topography, showing a "horn shape" with a high in the South and low in the East, with a thickness of 1,000–1,500 m. During this period, the fault succession developed and the activity intensity weakened, which had a slight impact on the sedimentation, and therefore the thickness of the Doba Formation is stable.

(4) Late Cretaceous first compression inversion (the end of K_2a Formation sedimentary period). Due to the collision between the African and European plates (Fairhead, 2009), the depression was compressed in the direction of NNW-SSE. On the seismic section, a regional angular unconformity reveals denudation due to uplift, and the strata arched up in the central and northern part of the depression (Figures 3, 6), indicating that the early normal faults underwent compressional inversion. This period is the first structural inversion in the Doseo depression and also the Santonian compression inversion event (84 Ma).

(5) Paleogene second strike slip inversion (the end of K_2b Formation sedimentary period). In this period, the depression was affected by the remote effect of the India-Eurasia plate collision (Fairhead, 2020), whereby compressional strike slip movement began. As a result, many new faults formed in the middle and south of the depression (Figure 6), whereas the rest were inherited. In the middle of the depression, an antiformal negative flower structure was formed by compression torsion, and the whole stratum was extruded and uplifted to form a larger angular unconformity, with more obvious denudation and folding (Figures 3, 6). The profile shows that most faults continued to develop until the Paleogene.

(6) After entering the stable subsidence period of the Paleogene, the active strike slip motion of the Central African Shear Zone stopped and the structural activity of the Doseo depression also stopped. The faults were deactivated, and the depression entered the filling and leveling stage. Under the structural framework of the uplift and depression, the Paleogene and Neogene developed a compensated alluvial fluvial filling system, which has continued until now, resulting in the lack of regional cover on the strata above the lower Cretaceous. The thickness of sedimentary strata in this period is small, generally no more than 500 m. The thickness of the strata in the east of the depression is 200–500 m, and the thickness of the strata in the west of the depression is less than 200 m. Drilling reveals that this period is associated with mainly fluvial facies deposition (Kong et al., 2019), and the lithology is mainly coarse-grained sandstone.

6 Discussion

6.1 Identification of two phases of strike slip movement

The two stages of strike slip movement explored in this paper are located in the second and fifth stages of the structural evolution of Doseo depression respectively. For a more detailed analysis of the

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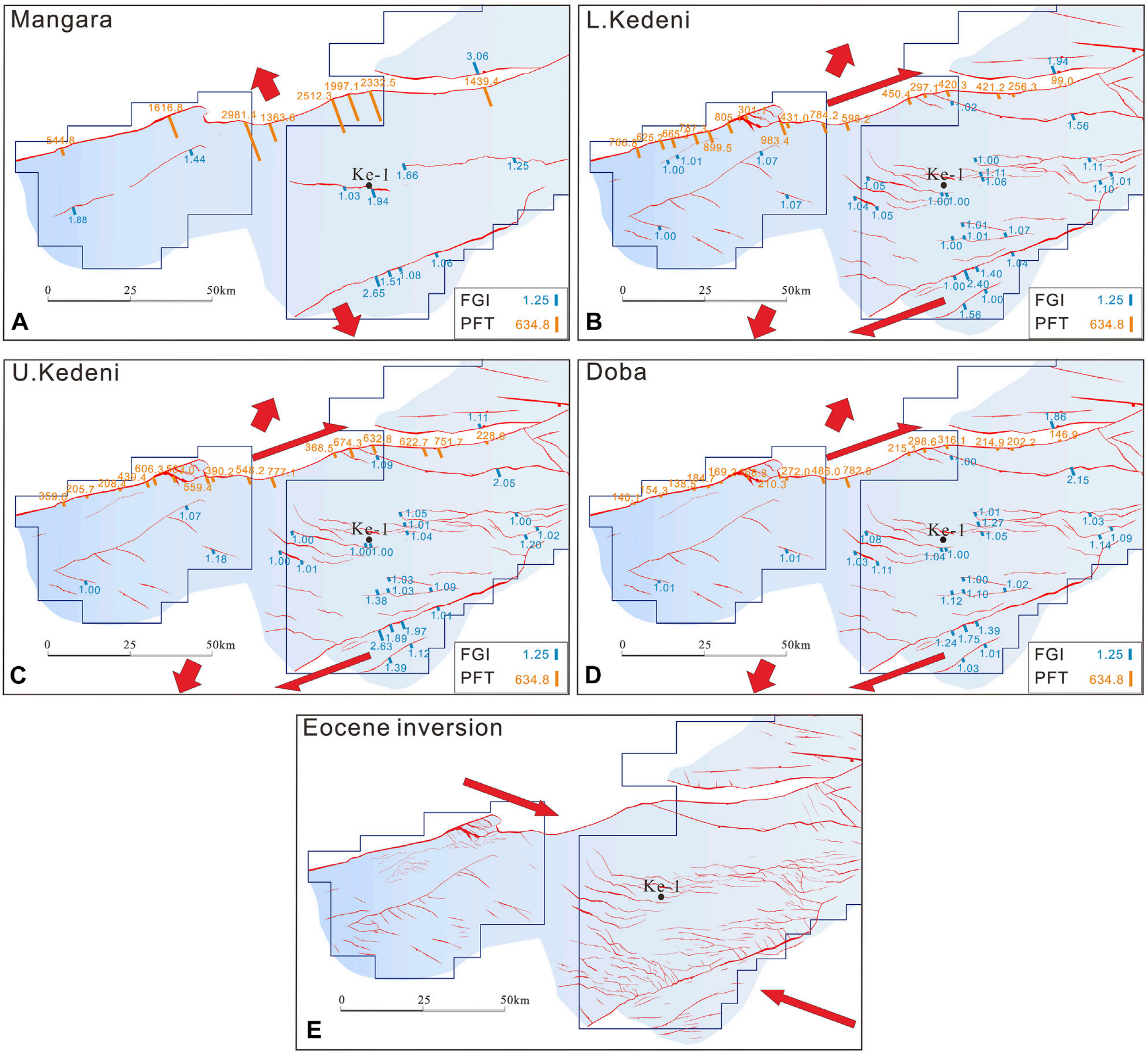

FIGURE 7
Plane distribution of paleo-fault throw and fault growth index during the first strike slip movement and fault system diagram of the second strike slip movement in Doseo depression. **(A)** Mangara Formation sedimentary period, **(B)** L. Kedeni Formation sedimentary period, **(C)** U. Kedeni Formation sedimentary period, **(D)** Doba Formation sedimentary period, **(E)** Eocene inversion. Faults in the study area (red lines), stress direction (red arrows), seismic data range (blue boxes), fault growth index (FGI), paleo-fault throw (PFT). The change of fault activity (Figure 5), combined with the regional stress field and the previous analysis of the evolution profile (Figure 6), reveals that the first strike slip motions occurred in the sedimentary period of the L. Kedeni Formation- Doba Formation sedimentary period. The depression was subject to superimposed stress of NE-SW extension and dextral strike slip. In the first strike slip faulting stage, the activities of the inner boundary fault, the southern sub sag, and the eastern part of the depression are relatively strong. On the boundary fault, the activities of the bending part of the right step are more intense.

fault activity characteristics and more precise division of fault activity periods, the fault spatial distribution in Doseo depression, relevant fault growth index, and paleo-fault throw in each sedimentary period are superimposed to analyze fault activity.

6.1.1 The first strike slip faulting stage

In the Early Cretaceous, with the rapid separation of the African Plate and the South American Plate (Guiraud et al., 2005), the regional geodynamic and tectonic environment changed. In response, the central South African block and the east North African block began to change from the early N-S extension to the dextral strike slip movement (Guiraud et al., 2005). This stage includes the Kedeni Formation and Doba Formation sedimentary periods.

During the Mangara Formation sedimentary period, the Doseo depression experienced an NNW-SSE extensional stress field, mainly forming two boundary normal faults controlling the development of the depression and a fault zone composed of several small-scale normal faults in the middle of the depression, and the faults were distributed in NEE direction. In terms of paleo-fault throw, the

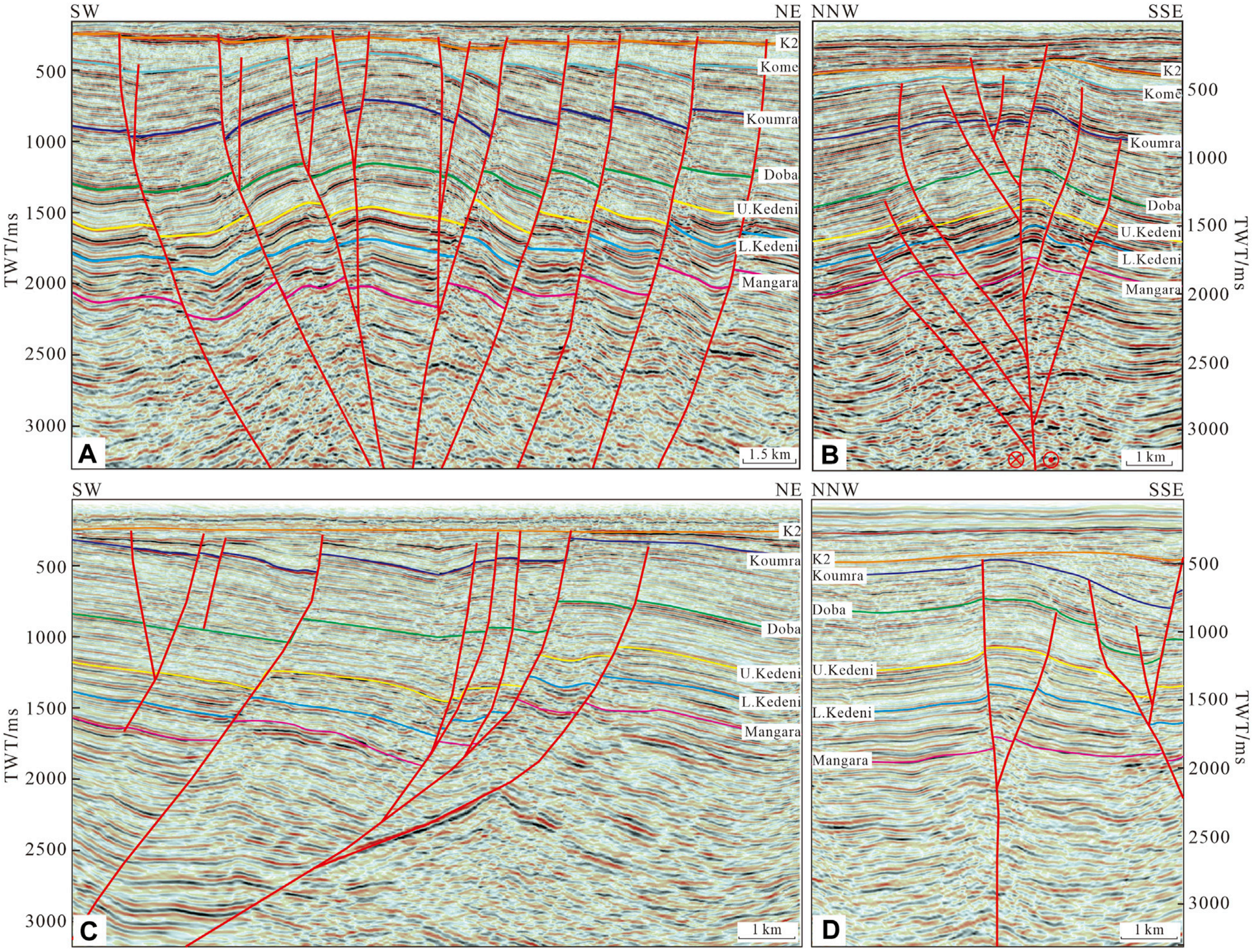

FIGURE 8
Seismic profile of two strike slip movements in Doseo depression. **(A)** En-echelon normal fault, Section D in Figure 1, **(B)** Composite flower structure, Section E in Figure 1, **(C)** Horsetail normal fault, Section F in Figure 1, **(D)** Positive flower structure, Section G in Figure 1.

boundary fault activity was strong at this time, and in the central part of the depression was greater than that in the West and East. Based on the fault growth index, some faults in the depression were strongly active at this time, such as the faults in the northeast depression and Southern sub sag. Generally, basin subsidence and sedimentation occurred in the hanging wall of the active fault. During the L. Kedeni Formation sedimentary period, the overall fault activity was not strong, although fault activity was slightly stronger at the bending part of the right step of the boundary fault, which suggests that the fault was subject to tilting extension and strike slip extension and that the whole depression was under a superimposed stress field of NE-SW extension and dextral strike slip. The fault activity during the deposition of the U. Kedeni Formation was similar to that during the deposition of the L. Kedeni Formation, with some inherited activity and an overall low rate of faulting. During the Doba Formation sedimentary period, fault activity was further weakened, although fault activity at the right step bending of the boundary fault was relatively stronger, indicating that the depression was still under a superimposed stress field of NE-SW extension and dextral strike slip at this stage, and that the stress field was weakened (Figure 7).

The first strike slip movement formed negative flower faults and en-echelon faults, which are typical characteristics of divergent-wrench faults (Zhang et al., 2015; Kong et al., 2019). The distribution of NWW-SEE en-echelon faults can be seen in the west of the central uplift zone of the Doseo depression under the strike slip extension (Figures 8A, C, 9). On the en-echelon fault section, there are upward arched negative flower shaped faults composed of positive faults. On the corresponding map view (Figure 9A), the North Fault dips southward, the South fault dips northward, and an anticline shaped uplift is formed between the faults. At the same time, a horsetail fault appears at the end of the strike slip fault in the eastern depression.

6.1.2 The second strike slip faulting stage

In the late Cretaceous, the continuous expansion rate of the Atlantic Ocean continued to decrease (Fairhead, 2020). With the gradual activity of the East African Rift and the Red Sea rift, the regional dextral shear compressive stress increased, and the Doseo depression began to enter the slow depression stage. In the late Cretaceous Koumra Formation sedimentary period, the Doseo depression was in the depression period, with stable stratigraphic

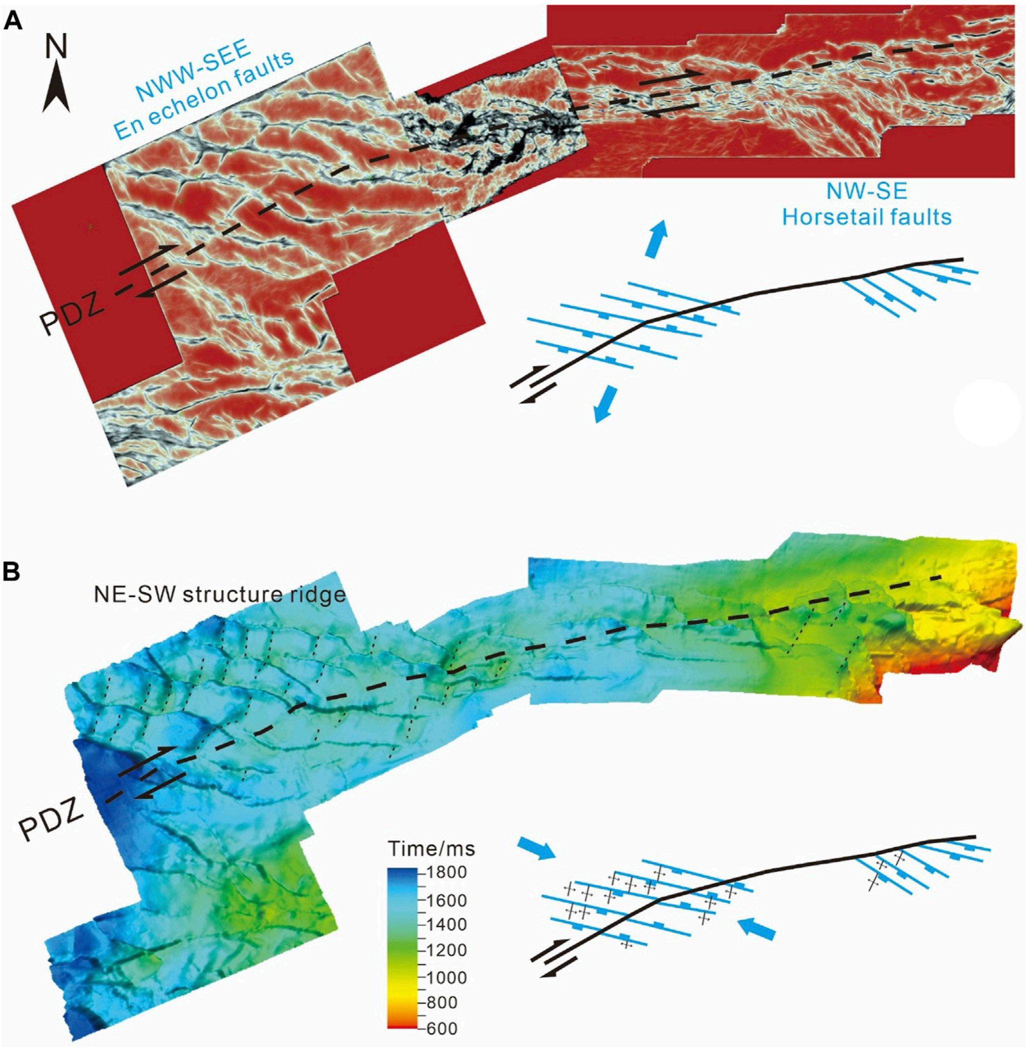

FIGURE 9
Plane distribution of faults in the Kedeni 3D area (PDZ represents Principal Displacement Zone). **(A)** Coherence map of top Kedeni Formation of NEE-SWW strike slip fault zone, **(B)** NE-SW structure ridge.

deposition and less fault activity, and no large-scale faults were formed. At the end of the late Cretaceous K_2 Formation sedimentary period, under the influence of the collision between the African plate and the European plate (Fairhead, 2009), the NNW-SSE compressive stress was formed. Structural inversion occurred in the Doseo depression, and compressive inversion occurred on the boundary fault of the northern steep slope zone, forming a faulted anticline, and the strata in the south of the depression were uplifted and denuded as a whole, forming an angular unconformity. This is known as the Santonian inversion (Fairhead, 2020). At the end of the Paleogene Eocene K_2b Formation sedimentary period, due to the remote impact of the collision between the Indian plate and the Eurasian plate (Najman et al., 2010), the compression direction changed to NW-SE, and dextral strike slip activity occurred in the Central African Shear Zone. During this period, strike slip inversion adjustment occurred in the Doseo depression, and the activities of boundary faults and fault zones in the middle of the depression induced the development of a large number of echelon oblique secondary faults intersecting with basement faults, resulting in new faults with high density and low strength (Figure 7E). In the late Paleogene, the activity of the Central African Shear Zone weakened, the fault activity stopped, and the strata of the Doseo depression were uplifted and leveled as a whole.

The change of fault activity (Figure 5), combined with the regional stress field and previous analysis of the evolution of the basin (Figure 6), reveals that the second strike slip movement occurred at the end of the K_2b Formation sedimentary period. The depression was subjected to NW-SE compressive strike slip tectonic motions at this time. In the second strike slip faulting stage, the fault activity in the south of the depression was strongest, followed by the middle, and therefore the flower structure and arch tension anticline were mainly developed in the south and middle (Figure 6). As the negative flower structure formed in the middle in response to the first strike slip faulting, the second strike slip faulting changed the negative flower structure into a composite flower structure (Figure 8B). In the south where the effect of the first

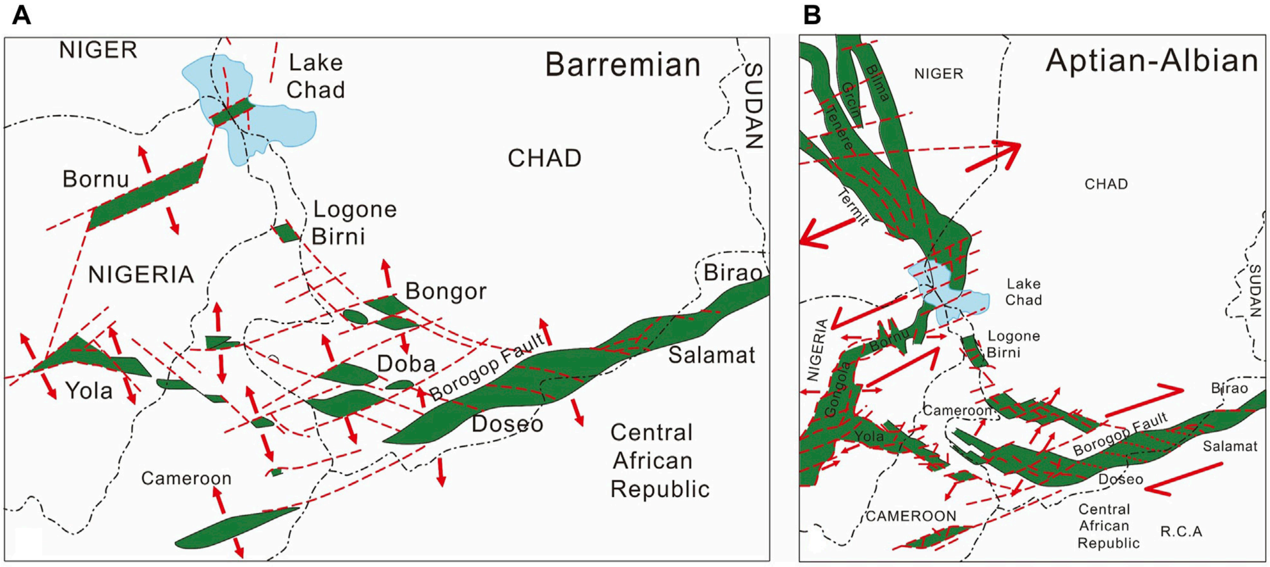

FIGURE 10
Geometric structure and stress field direction of the Doseo depression (modified according to Fairhead, 2020). **(A)** The Early Cretaceous Barremian, **(B)** the late Early Cretaceous Aptian-Albian.

strike slip faulting is weak, a typical positive flower structure can be seen (Figure 8D).

The second strike slip movement resulted in the structural inversion of the fault in the depression and formed the reversed fault. On the seismic profile, there are composite flower structures composed of reversed faults (Figure 8B), and in map view, there are NE-SW trending anticlines and faulted anticlines (Figure 9B), which mostly developed on pre-existing faults. NE-SW trending structural ridges also represent the formation of fault-folding structures under transpression (Figure 9B).

6.2 Dynamic mechanism of two-stage strike slip movement

6.2.1 The first strike slip faulting stage

In the early Cretaceous, the tectonic stress state mainly came from the expansion of the mid-Atlantic Ocean, resulting in a dextral strike slip movement in the Central African fault zone in the African continent and a sinistral strike slip movement in the West African fault zone (Binks and Fairhead, 1992; Fairhead, 2020). In the early stage, the eastern part of the African continent produced an extensional stress field in the direction of the meridional line, forming the initial rift (Yu et al., 2018). During the deposition of the Mangara Formation in the Early Cretaceous (145–125 Ma), the Doseo depression was stretched in an NNW-SSE direction and was in and experienced rapid north-south extensional fault subsidence. Three SSW-NNE normal faults were formed in the depression and controlled by boundary faults, a dustpan-like fault depression formed in the near East-West direction, which was steep on the north side and gently sloping on the south side (Figure 10A) (Zhang et al., 2015).

The first strike slip activity occurred in Aptian- Albian (125–111 Ma) in the Late Cretaceous, which was strike slip extension activity after the initial extensional phase of the Doseo depression. The eastern block of the African Continent moved northeastward and the Atlantic Ocean expanded, generating a tensile stress field in an approximate latitudinal direction, while the Central African fault zone was experiencing dextral strike slip movements and was superimposed by transform faults. The Central African basin then entered the main rift period (Figure 10B) (Zhang et al., 2018). At this time, the Doseo depression is under experienced a NEE-SSE-directed extension and was located in the dextral strike slip shear zone as a whole. The rapid subsidence of the depression was controlled by the boundary extensional strike slip fault. The boundary fault gave rise to secondary faults and the original faults successionally developed.

6.2.2 The second strike slip faulting stage

In the late Cretaceous (111–85 Ma), the tectonic stress state mainly came from the rapid expansion of the South Atlantic and the Indian Ocean. In the late Cretaceous, the African plate and Eurasian plate accelerated their collision (Fairhead, 2020). This rapid collision caused the Santonian compression event (84 Ma) (El Hassan et al., 2017), forming a nearly north-south compressive stress within the African plate. This compression resulted in inversion structures in many basins of the Central African Rift System (Warren, 2009). The Doseo depression was subjected to an NNW-SSE compression, resulting in a compression reversal. The early normal faults were compressed and reversed, forming anticlines and faulted anticlines (Figure 11A). The whole southern depression was uplifted and denuded, forming an angular unconformity.

The compression direction of the Doseo depression was still NNW-SSE until the Eocene. Due to the remote effect of the collision between the Indian and Eurasian plates, the Central African Shear Zone experienced dextral strike slip movement again (Figure 11B) (Fairhead et al., 2013). The transpression after compression occurred in Doseo depression, while other basins may also have

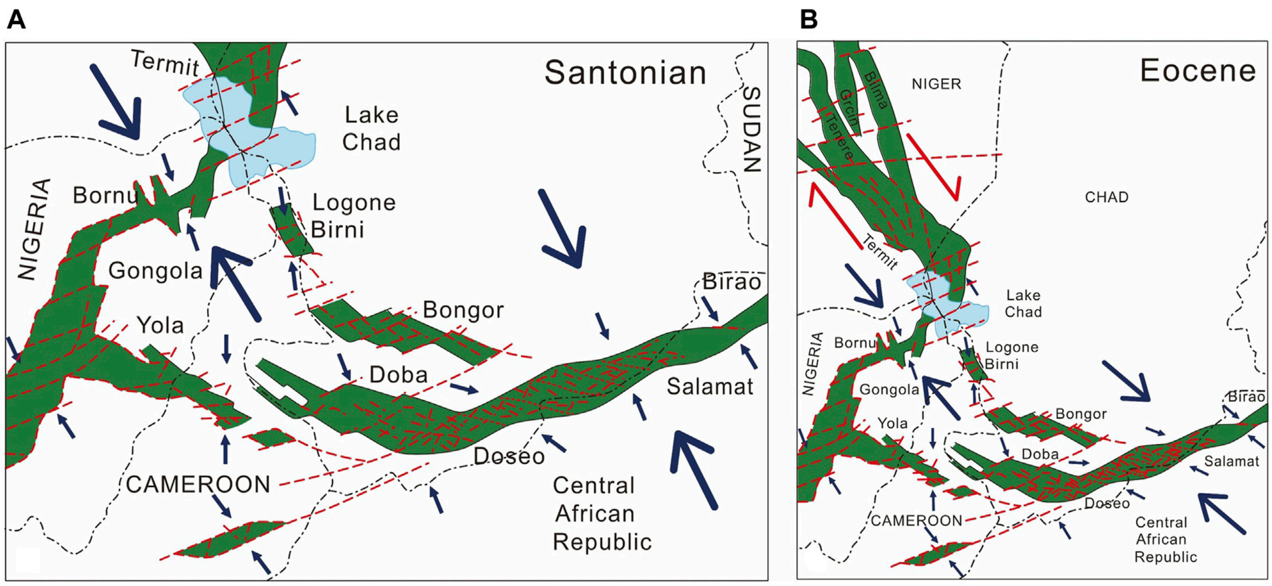

FIGURE 11
Geometric structure and stress field direction of the Doseo depression (modified according to Fairhead, 2020). **(A)** The Late Cretaceous Santonian, **(B)** Paleogene. Eocene.

experienced inversion (El Hassan and El Nadi, 2015). The basement fault exhibits dextral strike slip, and the shallow layer contains normal faults, which are arranged en-echelon in map view in the northwest and central part of the study area. Many small shallow faults in the depression were formed by strike slip inversion in this period. The compression direction of the Doseo depression was adjusted from NNW-SSE to NW-SE, and the second strike slip movement occurred at approximately 40 Ma.

6.3 Significance of two stages of strike slip movement

The two strike slip movements experienced by Dosoe depression are the first stage of strike slip tectonic movement under tilting extension and the second stage of strike slip tectonic movement under transform compression. The genetic mechanisms of the two strike slip movements were different, and faults with different properties were developed, so the impact of the two strike slip movements on the depression were completely different. The first stage of the strike slip movement mainly controlled the overall structure of the depression, especially the development of the sedimentary center, which made the depression form two sedimentary centers, the East and the West. The second stage of strike slip tectonic movement mainly controlled the formation of some inversion structures and southwest northeast trending anticlines and fault anticlines. The superposition of strike slip structures in the two stages led to the extensive development of composite flower structures in the sag.

The development of source rocks and reservoirs was controlled by different faulting periods in the basin. The early depression-controlled normal fault underwent strike slip inversion during the depression period of the basin and became the main oil source fault. The strike slip inversion structural belt controlled the development of structural traps, and then controlled the enrichment of oil and gas (Hu et al., 2007).

7 Conclusion

This study aimed to clarify the tectonic development of Doseo depression in the Central African Rift System. Based on seismic interpretation, calculation of fault growth index and paleo-fault throw, balanced cross-section restorations, and integrated analysis, the conclusions are as follows:

The Doseo depression experienced five main tectonic movements: the early Cretaceous rifting period (Mangara Formation sedimentation period), the Early Cretaceous fault depression period (Kedeni Formation- Doba Formation sedimentation period), the Late Cretaceous thermal subsidence period (Koumra Formation sedimentation period), the Late Cretaceous first compression inversion (at the end of the K2a Formation sedimentation period), and Paleogene second strike-slip inversion (at the end of the K2b Formation sedimentation period).

The two stages of strike slip movement occurred in the second and fifth stages of the tectonic evolution of the Doseo depression. In the first stage, the depression was subjected to NE-SW extension and dextral strike slip superimposed stress, which is a strike slip tectonic movement under tilting extension, forming a negative flower shaped fault and en-echelon shaped fault. In the second stage, the depression was subjected to NW-SE compressional strike slip tectonic movement, which was a strike slip tectonic movement under transpression, forming a reverse structure. The strike slip mechanism of the two stages was different, and the impact on the depression is also completely different. The first stage of strike slip tectonism controlled the overall structure of the depression, especially the development of the sedimentary center, while the second stage of strike slip tectonism mainly controlled the formation of some inversion structures and SW-NE trending anticlines and faulted anticlines. These anticlines and faulted anticlines are a favorable play for oil and gas accumulation. The superposition of two stages of strike slip tectonics led to the extensive development of composite flower structures in the depression.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XZ conceived the idea; LD conducted the analyses; ZN, provided the data; KX, analysed the data; LW, YD, SC, LW, and XZ interpreted the results; all authors contributed to the writing and revisions.

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Conflict of interest

The authors XZ, LD, KX, YD and LW were employed by PetroChina Research Institute of Petroleum Exploration and Development. Authors LD, ZN, and LW were employed by China National Oil and Gas Exploration and Development Corporation Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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